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THE SECONDARY STANDARDIZATION OF RADIO WAVEMETERS

The purpose of this Circular is to give a detailed description of the comparison of two wavemeters, one of which has already been standardized in terms of the frequency or wave length corresponding to each scale reading. This comparison is called secondary standardization as distinguished from primary standardization, which is the comparison of a wavemeter with some more fundamental standard of frequency or wave length such as a vibrating tuning fork or a pair of parallel conductors in which standing electric waves are set up. The quantities, frequency and wave length, in terms of either of which a wavemeter may be standardized, are readily converted from one to the other by means of the relation

$$c = \lambda f$$

in which c is the velocity of electromagnetic waves, 2.998×10^8 meters per second, λ is the wave length in meters, and f the frequency in cycles per second. Radio frequencies are usually more readily given in kilocycles per second, one kilocycle being as the name implies, equal to one thousand cycles. At the present time most wavemeter standardizations are in terms of wave length. For several reasons, however, it is more satisfactory to deal in terms of frequency, and this is now widely recognized as good practice. Frequency rather than wave length is referred to in this Circular. Where equations are used involving either quantity they are given in terms of both quantities.

Wavemeters are of two main types, which correspond in operation to receiving sets and transmitting sets respectively.

Wavemeters of the Receiving Type. The receiving type is the more common. Such an instrument consists of a resonating circuit, with either the condenser or the inductor or both variable, and a device to indicate resonance. The device to indicate resonance is usually a radio-frequency galvanometer, a detector and telephone receivers, or a battery lamp.

The elementary process of standardizing all wavemeters of the receiving type is the same. It consists in measuring by means of a standard wavemeter the frequencies emitted by a generator of continuous waves which is tuned successively to resonance with the wavemeter under test at different settings of the scale of the latter. For a scale graduated in degrees, suitable points

for standardization are 10°, 50°, 90°, 130° and 170°. For a scale graduated in hundredths, readings may be made at 5, 25, 50, 75 and 95, or, if, as is frequently the case, the least division represents two hundredths, they may be made at 10, 30, 50 70 and 90. The first step is to loosely couple the wavemeter under test to the generator. The wavemeter is set at the desired scale reading and the generator is then tuned until the indicating device of the wavemeter shows maximum current. If the power output of the generator remains constant while the generated frequency is being changed, the generator and wavemeter are in tune when maximum current is obtained. If, however, the power varies with the emitted frequency, the rate of change of current in the wavemeter will depend not only on the approach to or departure from resonance but also on the variation of the power. The setting for maximum current, being determined in part by this latter factor, will consequently differ more or less from the true setting for resonance.

To guard against such an error it is necessary after tuning the generator to the wavemeter to tune the wavemeter to the generator and notice whether or not the setting of the wavemeter after it is tuned is the same as before. If it is the same, it is evident that the output of the generator was not changing enough to introduce an error. For, except in the case (which will be discussed later) in which the wavemeter reacts on the generator, the tuning of the wavemeter to the generator is merely the tuning of a circuit to resonance with incoming waves of constant frequency and amplitude. Hence the current (or its square) will describe the true resonance curve. If this curve has its peak at the same wavemeter setting as the apparent resonance curve, wavemeter and generator are truly in resonance at that setting. But if the setting of the wavemeter after it is tuned to the generator is different from what it was before, then some means must be found of bringing the generator and wavemeter truly in resonance at the desired setting. It is of course best, if possible, to eliminate the source of error, namely the change in the output of the generator. Sometimes this can be done by changing the ratio of inductance to capacity in the circuit of the generator. When, however, the behavior of the generator can not be improved, allowance must be made for the irregularities. That is, the generator must be tuned not to show apparent resonance at the chosen wavemeter setting and true resonance somewhere else but to show true resonance at the chosen setting and apparent resonance at some other point.

For example, let the wavemeter be set at 10° and the generator tuned to apparent resonance with it. Now the wavemeter is tuned to the generator and tunes in not at 10° but, let it be assumed, at 10°.5. Generator and wavemeter are now truly in resonance at 10°.5 (unless as before stated the wavemeter is

reacting on the generator). But it is desired to have them in resonance at a wavemeter setting of 10°. The emitted frequency can be changed by making minute changes in the setting of the generator and the desired condition obtained by a series of approximations. Or, since the true resonance point was observed to be 0°.5 higher than the apparent resonance point, the generator may be tuned to apparent resonance with the wavemeter set at 9°.5 and the true resonance point will then probably be found at about 10°.

Change in the output of the generator and consequent distortion of the resonance curve will result from too close coupling between wavemeter and generator. This distortion, like the similar effect just described, will reveal itself when the wavemeter is tuned to the generator. For this effect includes with a change in the power output of the generator a constraint on the emitted frequency, since forced vibrations in the frequency of the wavemeter are fed back into the generator. When this constraint is varied by changing the wavemeter setting, the emitted frequency is changed and this appears in tuning the wavemeter. Generally, however, any serious reaction of the wavemeter on the generator will show itself when the generator is being tuned to the wavemeter. A typical effect is the occurrence of two apparent resonance points, one obtained when the emitted frequency is increased toward resonance, another when it is decreased toward resonance. As the emitted frequency is varied through one of these points, the current will rise normally to a certain value, then drop precipitately, as if some kind of an elastic limit had been reached and the resonant condition had snapped. The remedy is, of course, to decrease the coupling.

The necessity for tuning the wavemeter to the generator is one reason why the extreme points of the scale, 0° and 180° or 0 and 100 divisions, are not chosen as points of a standardization. For, if by tuning the generator to the wavemeter, apparent resonance is obtained at either extremity and the frequency required for true resonance is just off the wavemeter scale, tuning the wavemeter will nevertheless give maximum current just at the extremity. Another reason for avoiding the end points lies in the fact that at these points the calibration curve is at a minimum or a maximum and therefore flat. This makes for broad tuning and renders these and neighboring points of the wavemeter scale unfit for use in measurement. An additional cause for avoiding the lower part of the scale is that in this region errors of reading and other errors that are absolute in their nature introduce a much greater percentage of error than elsewhere on the scale.

In standardizing wavemeters in which the resonant circuit consists of a fixed condenser and a continuously variable in-

ductor a difficulty is encountered in the fact that a change in the self inductance of the inductor is likely to be accompanied by a change in the mutual inductance between wavemeter and generator, causing a change in the current in the wavemeter circuit which has nothing to do with resonance. To minimize this difficulty such wavemeters are customarily made with a coupling coil of a very few turns in a plane perpendicular to the face of the movable coil. This coil is in series with the variable inductor. By means of it, the wavemeter can be coupled to the generator and coupling between the generator and the movable coil can be kept at a minimum. The necessity of having to take this precaution is a disadvantage of this kind of wavemeter.

The standardization of wavemeters in which resonance is indicated by a crystal detector and telephone receivers has several features not shared with the standardization of wavemeters of other types. In the first place, in order to produce an audible signal in the telephones, the continuous waves emitted by the generator must be modulated in some way. Sine-wave modulation is the most desirable, since it produces the fewest extra frequencies accompanying the frequency of the main wave. When the plate voltage required by the electron tube is of a suitable value, modulation may be obtained by superposing the sixty-cycle line voltage on the direct-current plate-voltage. Modulation may be obtained also by inserting a chopper in the grid lead of the generator.

Tuning to maximum sound is not only a somewhat inaccurate process but is also fatiguing if continued for any length of time, the fatigue rendering the ear still less sensitive to changes in sound intensity and still further diminishing the accuracy of setting. It is often possible to avoid this trouble by inserting in series with the detector and telephone receivers a sensitive direct-current galvanometer and tuning to the maximum deflection of this instrument. Before this procedure can be used in a calibration it is necessary to find whether or not the introduction of the galvanometer changes the calibration of the wavemeter. If there is such a change it may be expected to be most marked where the capacity in the circuit is small. Consequently if measurements agree which are made at points where the capacity is small, with the galvanometer first inserted and then omitted, the galvanometer may safely be used to indicate resonance throughout the standardization. The possibility of error as a result of introducing a direct-current galvanometer is particularly small if the circuit containing detector and telephones is merely coupled to the wavemeter coil or joined at one point only to the wavemeter circuit. It may be well to remark that when a galvanometer having several scales is tested in this respect, and one scale proves satisfactory, it does not follow that all the scales are satisfactory.

Even though a galvanometer is used, it is a good plan if not too inconvenient, for the observer to keep the telephone receivers on his head throughout the calibration in order to duplicate to this extent the conditions of use and also because reaction of the wavemeter on the generator is more evident from the sound in the telephone receivers than from the deflection of the galvanometer. If, however, the observer is not interested in listening to the sound in the telephone receivers, he may dispense with modulation while using the galvanometer to indicate resonance. In some cases this will improve the performance of the generator.

In making a test with a detector and telephone receivers, as in other cases, after the generator has been tuned to the wavemeter the wavemeter is tuned to the generator as has been described.

In some wavemeters the device used to indicate resonance is not joined to the wavemeter circuit but is inserted in one or two conducting turns inductively coupled to the wavemeter coil. In this case the coupling between the generator and the detecting circuit must be kept small in comparison with the coupling between the generator and the wavemeter coil or between the wavemeter coil and the detecting circuit. Otherwise an error is introduced. The detecting turn or turns should be kept on the opposite side of the inductor from the generator and, as much as possible, in what may be called the "shadow" of the inductor.

The generator and the wavemeter under test having been brought accurately into resonance, the first part of the measurement is complete. The wavemeter is now detuned. Detuning is necessary in order to keep the current in the wavemeter under test from acting on the standard wavemeter when the latter is brought up. Time will be saved if, instead of merely throwing the wavemeter out of resonance, the operator sets it at the reading of the next point of the standardization. The wavemeter under test is now moved aside and the standard wavemeter is brought up to the generator and tuned to resonance. As before, care must be taken to avoid too close coupling.

The scale readings of the standard wavemeter corresponding to the chosen readings of the condenser under test are recorded, and the wave frequencies are read from the calibration curve of the standard wavemeter.

Two runs should be made over the entire range of each standardization. In testing a good wavemeter using a galvanometer to indicate resonance, corresponding readings should for the most part be found in agreement within two-tenths of one per cent. and within one per cent. when a detector and

telephone receivers are used. If the demands apt to be made on the wavemeter tested warrant this degree of accuracy, all readings failing to agree within these limits should be repeated.

Wavemeters of the Transmitting Type.- The standardization of wavemeters of the transmitting type is simpler in principle than that of wavemeters of the receiving type, but in practice it is apt to be more difficult. Such wavemeters consist of a condenser and an inductor, one or both variable, and an exciting device comprising generally a battery and a buzzer coupled or connected to the wavemeter circuit proper. The make-and-break of the buzzer excites the wavemeter by impact and waves are emitted whose frequency is regulated by the wavemeter setting. The frequency of the waves emitted at each setting of the calibration is then measured by means of the standard wavemeter. The difficulty is in the fact that the power output of the buzzer-excited wavemeter is so small that it is hard to detect the minute current induced in the standard wavemeter. In some cases the detection of this current may even be impossible. The wavemeter may under these conditions be compared with a receiving set whose frequency at each setting under assigned operating conditions has been determined by comparison with the standard wavemeter. Or it may be equipped with a device to indicate resonance and calibrated as a wavemeter of the receiving type. A difference of several per cent. may, however, exist between the calibration of a wavemeter obtained in the manner just named and the calibration of the same wavemeter when excited by a buzzer.

Two runs should be made and doubtful readings repeated. Definite limits within which agreement may be expected can not be stated.

Measurement of Decrement and Resistance.- It is sometimes desired to measure the decrement or the high-frequency resistance as well as the frequency of a wavemeter. This measurement is made by the use of one of the equations given below. The symbols used are explained in the discussion following.

Decrement	Resistance
$\delta = \pi \frac{R_1}{\omega_r L} \frac{I_1}{I_r - I_1}$ (1)	$R = R_1 \frac{I_1}{I_r - I_1}$ (2)
$\delta = \pi \frac{\pm(C_r - C_1)}{C_1} \sqrt{\frac{I_1^2}{I_r^2 - I_1^2}}$ (3)	$R = \frac{\pm(C_r - C_1)}{\omega_r C_r C_1} \sqrt{\frac{I_1^2}{I_r^2 - I_1^2}}$ (4)
$\delta = \pi \frac{\pm(L_r - L_1)}{L_r} \sqrt{\frac{I_1^2}{I_r^2 - I_1^2}}$ (5)	$R = \pm \omega_r (L_r - L_1) \sqrt{\frac{I_1^2}{I_r^2 - I_1^2}}$ (6)
$\delta = \pi \frac{\pm(\omega_r^2 - \omega_1^2)}{\omega_r^2} \sqrt{\frac{I_1^2}{I_r^2 - I_1^2}}$ (7)	$R = \frac{\pm L(\omega_r^2 - \omega_1^2)}{\omega_r} \sqrt{\frac{I_1^2}{I_r^2 - I_1^2}}$ (8)
$\delta = \pi \frac{C_2 - C_1}{C_2 + C_1} \sqrt{\frac{I_1^2}{I_r^2 - I_1^2}}$ (9)	$R = \frac{1}{2\omega_r} \frac{C_2 - C_1}{C_2 C_1} \sqrt{\frac{I_1^2}{I_r^2 - I_1^2}}$ (10)
$\delta = \pi \frac{\pm(\lambda_r^2 - \lambda_1^2)}{\lambda_1^2} \sqrt{\frac{I_1^2}{I_r^2 - I_1^2}}$ (11)	$R = \frac{cL}{2\pi \lambda_r} \frac{\pm(\lambda_r^2 - \lambda_1^2)}{\lambda_1^2} \sqrt{\frac{I_1^2}{I_r^2 - I_1^2}}$ (12)

All of these equations assume a constant electromotive force during the change in the circuit which causes the change in effective current from I_r to I_1. This means that the coupling between wavemeter and generator does not change and is loose enough that the current in the wavemeter does not react appreciably on the current in the generator, and that the power output of the generator is constant in other respects. A further assumption is that the decrement of the generator is zero, that is, undamped waves are emitted. This assumption is implied in the equations for resistance as well as in those for decrement. The condition that the decrement of the waves be zero includes not only damped but also modulated waves, for the latter may be considered to have an equivalent decrement.

Equations (1) and (2) represent the resistance-variation method. R_1 is the value of a non-inductive resistance added to the wavemeter circuit. R is the resistance of the circuit without this addition. I_r is the current in the wavemeter when it is tuned to resonance with the generator at a frequency indicated by ω_r, where ω_r is 2π times the frequency of the emitted waves.

I_1 is the current reduced by the addition of R_1. L is the inductance in the wavemeter circuit. This method has the advantage that R_1 can be measured very accurately with a Wheatstone bridge, much more accurately in general than C, L, or ω. The difficulty in applying the method lies in the fact that it is often not possible to insert a resistor in a circuit without seriously changing characteristic quantities of the circuit other than the resistance. In other cases, however, the design of the wavemeter permits this to be done. It is necessary that the insertion of the resistor shall not only do no violence to the electric properties of the wavemeter but also not jar or otherwise disturb the circuit enough to cause a change in the coupling between wavemeter and generator. At the point where the circuit is broken for the insertion of the resistor mercury wells should be attached to the free ends, and the resistor, in the shape of a link, should be laid in these. The condition of no added resistance is obtained by inserting a link whose resistance is negligible. If one side of the wavemeter is grounded during use, the resistor should be inserted on that side. Preferably, also, the ammeter or current-square meter should be on the same side. Grounding is helpful, but, if the instrument is to be used ungrounded, it should be tested the same way. Shielding of the entire apparatus in a cage of small mesh wire screening also adds to the accuracy of the process. It should be noticed that, since I, the current, enters to the same power in numerator and denominator in all the equations stated, it is necessary only that the indicating device give readings proportional to the current or its square, not necessarily equal to one of them. Each determination of decrement or resistance should be made with not less than three different inserted resistors. Good results are obtained when the values of inserted resistance are so chosen that one of them about halves the deflection with no added resistance and the other two, if three are used, give deflections on either side of this.

After every reading of a deflection, the zero of the current-measuring instrument, that is, the reading with the wavemeter circuit broken, should be read, and between the insertions of two resistors a reading should be taken of the deflection without added resistance. A value of the decrement or resistance of the circuit is obtained for each value of R_1 chosen, and these values are then averaged. No rule can be stated for the nearness of agreement to be expected, for this is largely determined by the construction of the wavemeter.

Equations (3) to (12) inclusive, represent different aspects of the reactance-variation method, of which the general equation is:

$$R = X_1\sqrt{\frac{I_1{}^2}{I_r{}^2 - I_1{}^2}}$$

where X_1 is the reactance added to the circuit by detuning it sufficiently to reduce the current from I_r to I_1. The choice between them is determined by consideration as to which of the quantities necessary for a solution is most readily dealt with. Equations (5) and (6) are practically excluded by the fact already mentioned that a variation in the inductance is almost certain to be accompanied by a variation in the coupling between wavemeter and generator. It is to be noted that this source of error is much greater in measurements of decrement or resistance than in measurements of wave length. In the latter case, the change in coupling causes a change in current, which in turn causes a displacement of the apparent resonance point. The error is thus introduced in a secondary manner. In measuring decrement or resistance, however, the change in current affects the result immediately and the error is much graver.

In any of these equations, from (3) to (12), the solution is simplified if $I_1{}^2$ is taken as $\frac{1}{2}I_r{}^2$. Then the term in I becomes unity and its coefficient measures the decrement or resistance. In equations (3) and (4), the change that causes the current drop is a detuning of the wavemeter condenser. The terms in C include the coil capacity as well as the condenser capacity. Equations (9) and (10) are modifications of (3) and (4). In (9) and (10) the capacity in the circuit is varied from a value C_1, giving a current I_1, upward through the resonance point to a value C_2 on the other side at which the current again has the value I_1^2. Since C_2-C_1 will be approximately twice C_r-C_1, the importance of an error of reading will be halved by taking the wider range of capacity variation. A more important advantage lies in the fact that the condenser can be set much more precisely at a point on the side of the resonance curve than at its peak.

Equations (7) and (8) are the same essentially as equations (11) and (12). The change indicated by the equations is in the frequency or wave length to which the circuit is resonant, and not the frequency or wave length of the waves emitted by the generator. The quantity c in equation (12) is the velocity of electromagnetic waves, very nearly 3×10^8 meters per second.

It has been stated earlier that the values of current used need be in terms of no defined unit. No units of any kind need be specified in equations (3), (5), (7), (9) and (11) for the same reason that applies to the values of current, viz., that the quantities involved enter to the same power in numerator and denominator. In the other equations, R and R_1 are in ohms, C in farads, L in henries, λ in meters, c in meters per second, and ω, since it is equal to 2π times the frequency, in radians per second. The plus-or-minus sign in equations (3) to (12) inclusive indicates merely that, whether the variation in reactance is effected by an increase or by a decrease capacity, inductance, etc., the decrement and resistance are always positive.

Several determinations should be made of each decrement or resistance measured. Different points on the scale of the current-measuring instrument should be used in order to reduce the effect of any local departure from the current or current-square law which the instrument is intended to follow. I_1^2 may always be chosen as equal to $\frac{1}{2}I_r^2$, and generally should be so chosen in order to simplify the calculations. The use of different parts of the scale can be effected by varying the coupling between generator and wavemeter between successive determinations of decrement or resistance.

The standardization of the condenser and the inductor of the wavemeter circuit as separate parts is described in Letter Circular No. 77, "The Comparison of Condensers at Radio Frequencies," and No. 76, "Standardization of Inductors at Radio Frequencies." For a comprehensive treatise on radio measurements, the reader is referred to Circular 74, of the Bureau of Standards, "Radio Instruments and Measurements." Copies of this publication may be purchased at sixty cents a copy from the Superintendent of Documents, Government Printing Office, Washington, D.C.

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